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Spring 2020

Custom 3D Printed Orthotic

Dakota Kirtley
dlk79@zips.uakron.edu

Andrew Wiles
aww29@zips.uakron.edu

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Custom 3D Printed Insoles

Andrew Wiles, Dakota Kirtley

Department of Mechanical Engineering

Honors Research Project

Submitted to

The Williams Honors College
The University of Akron

Approved:

Date: 05/03/2020
Honors Project Sponsor (signed)

Jae-Won Choi
Honors Project Sponsor (printed)

Date: 05/08/2020
Reader (signed)

Nathan Kemper
Reader (printed)

Date: 05/01/2020
Reader (signed)

Ronald E. Gauding
Reader (printed)

Accepted:

Date:
Honors Department Advisor (signed)

Honors Department Advisor (printed)

Date:
Department Chair (signed)

Department Chair (printed)

Custom 3D Printed Orthotics
Group 49
By Andrew Wiles and Dakota Kirtley

Class of 2020
The University of Akron

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Executive Summary

In a world of ever increasing options, quick and efficient customization of products is paramount. This project focuses on customization of orthotic inserts. All too often, consumers overpay for orthotic inserts that A) are not custom, and B) wear out too quickly. In the past decade, the continuation of development in the areas of solid modeling, 3D printing, and other types of rapid prototyping have made it easier than ever to achieve high levels of customization.

There currently exists some big name manufacturers with ties to pressure mapping and custom orthotics. However, these solutions are not without their issues. These custom orthotics tend to be overpriced, not truly custom, and don't provide any more support than standard orthotics.

The goal of this project is to expand on this idea of pressure mapping, and more completely combine the technologies at work to create a more customized, longer-lasting orthotic. The prototype consists of a wood platform for patients to stand on, with a PLA plastic template for placing 10 Tekscan Flexiforce pressure sensors. The prototype fits a men's size 10.5 shoe, but additional templates could be created to fit other shoe sizes.

By utilizing the aforementioned pressure sensors, 10 data points are taken across the entirety of a patient's foot (3 rows of 3, and a tenth placed at the center of the heel). These pressure sensors output a voltage difference based on the amount of pressure applied at that point. For the purposes of this project, it is necessary to convert the voltage output to a pressure, and subsequently to a value for the height at that point on the orthotic. While this seems a simple process, it is necessary to normalize that data so that all data is relative to its own self-contained set of data points. This is necessary due to weight differences in patients. Without normalization of data, the same foot for a patient that weighs 150lbs would vary greatly for the same foot for a patient that weighs 250lbs.

From a 3D modeling standpoint, a model template is necessary. Using a "standard" aspect ratio of a foot, the overhead view of the template model shape can be obtained. Next, the model can be segmented into four (4) pieces using planes. Each plane is given a profile of the foot contour at that plane using a series of points on a spline. After this, the model is ready to receive custom data.

Once the data is obtained, it can be tabulated and normalized using Microsoft Excel and imported into Autodesk Fusion 360 using the "Import XYZ Data" feature. This feature utilizes data from Excel to create curved sketches. Each segment plane will receive its sketch contour from this data, and a lofted cut is used to obtain the overall contour of the orthotic. The system is then validated by placing the 3D printed orthotic over the pressure sensors, and re-measuring the pressure distribution of the patient, to analyze if pressure has been effectively redistributed.

Acknowledgements

The authors of this paper would like to give special thanks to the following individuals and organizations, without whom, the resources, insight, and time that went into this project would not have been possible:

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Introduction

Orthotic insoles serve a multitude of purposes. There are three essential areas they can be applied to; sport, medical, and comfort. The largest and the fastest growing market is the comfort market. According to PR Newswire, the custom orthotic industry is estimated to reach 3.5 billion USD by the end of 2020. The biggest driver of this increase is the comfort market. Research shows that obesity in the United States and around the world is on the rise and with that comes the need for orthopedic support devices. Orthotic insoles can be developed for comfort and offer more support and cushion to an individual in their everyday life. One problem with the industry currently is limited ability to make customizations to off-the-shelf insoles.

One current option for achieving custom orthotics is offered by *Dr. Scholl's* at various retail locations. At these kiosks, customers can stand on a pressure mapping platform that takes pressure readings and suggests the model of insole that most closely resembles the customer's foot. The kiosk and example of its pressure reading can be seen in Figures 1 and 2, respectively.

Figure 1: Dr. Scholl's Kiosk

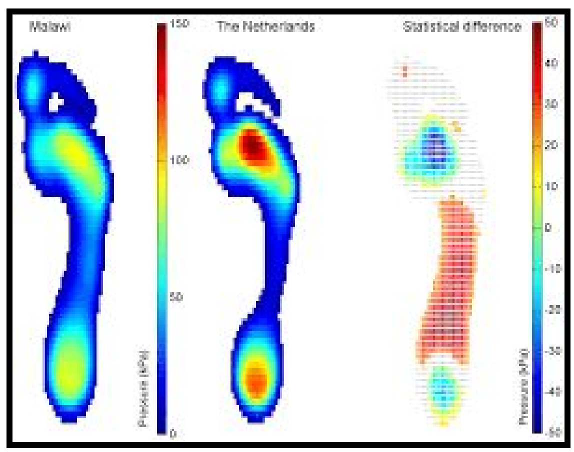


Figure 2: Continuous Pressure Sensor Reading

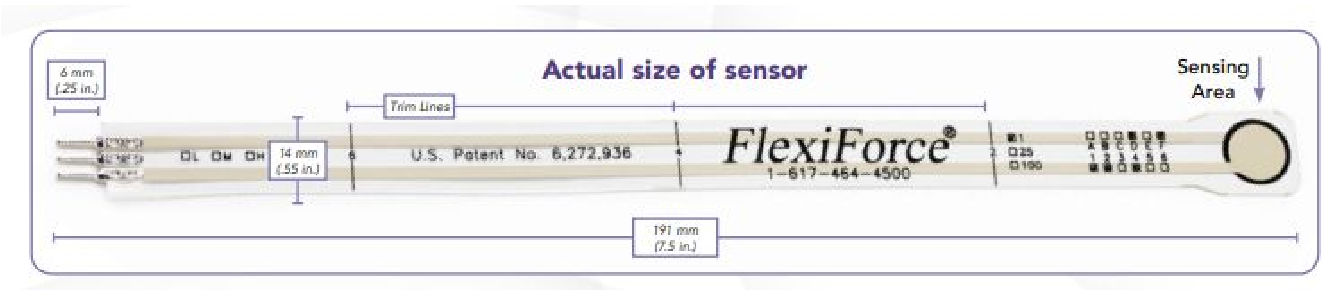
The problem is that these orthotics are overpriced and provide underwhelming support, according to *The Foot and Ankle Center of Washington*. These insoles are simply "close enough" to the custom fit that customers expect and deserve. From a manufacturing and profitability standpoint, it makes sense that *Dr. Scholl's* would only manufacture a finite number of custom fit insoles. However, as 3D modeling and rapid prototyping continues to develop out of its infancy, it becomes increasingly necessary to move away from mass production and delve into the possibilities that come with these technologies. In doing this, companies can put the customer above company profits and explore just-in-time manufacturing.

Right now there is a huge opening in the market to apply 3D printing to the custom orthotic industry. With advances in the range of materials to be 3D printed, the door is wide open to test and develop an entirely custom orthotic for every individual in need of one. The goal of this research project was to utilize pressure sensors and 3D printing to develop a streamlined process for creating the most customizable orthotic shoe insert possible.

<u>Technical Issues</u>

1. **Pressure Sensing**

Using the *FlexiForce* sensor depicted in Figure 3, the pressure at 10 different locations under the foot was recorded simultaneously. To collect this data, a wooden platform was built that housed a 3D printed template for the pressure sensors. The template sat flush with the top of the platform. A 3D rendering of this platform can be seen in Figure 4.



<u>Figure 3: Depiction of FlexiForce Pressure Sensor</u>

<u>Figure 4: 3D Rendering of Platform</u>

On the 3D printed template were 10 locations for sensors to be placed. The sensors were arranged as shown in Figure 5. The pattern consisted of 3 rows of 3 down the top of the foot and a tenth sensor directly in the center of the heel. We chose the locations based on the recommendation from our reader, Nathan Kemper, who holds a Bachelor of Science in Biomedical Engineering, and is now enrolled in med-school, pursuing a career as a doctor.

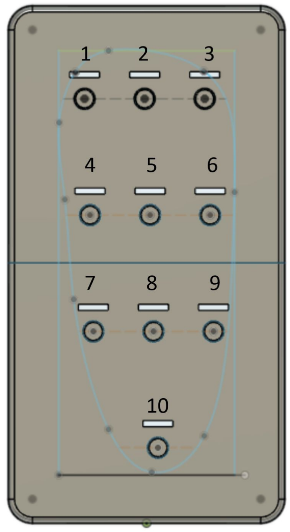


Figure 5: Layout of Flexiforce Sensors and Projection of Orthotic

To discuss the pressure sensors and data recorded, it should first be noted how data acquisition was achieved. Data was collected using an Arduino Mega 2560, the *FlexiForce* sensors discussed previously, a breadboard, a 47 pF capacitor, and a 100 kΩ resistor. The bread board was used to create a common power source and common ground for each series consisting of the above mentioned components. A total of 10 series were used (one for each sensor used). The sensors were wired to the common power source coming from the 5V that the Arduino provides. They were also wired to the common ground that the Arduino provides. A picture of the recommended circuit for the sensor is depicted below in Figure 6.

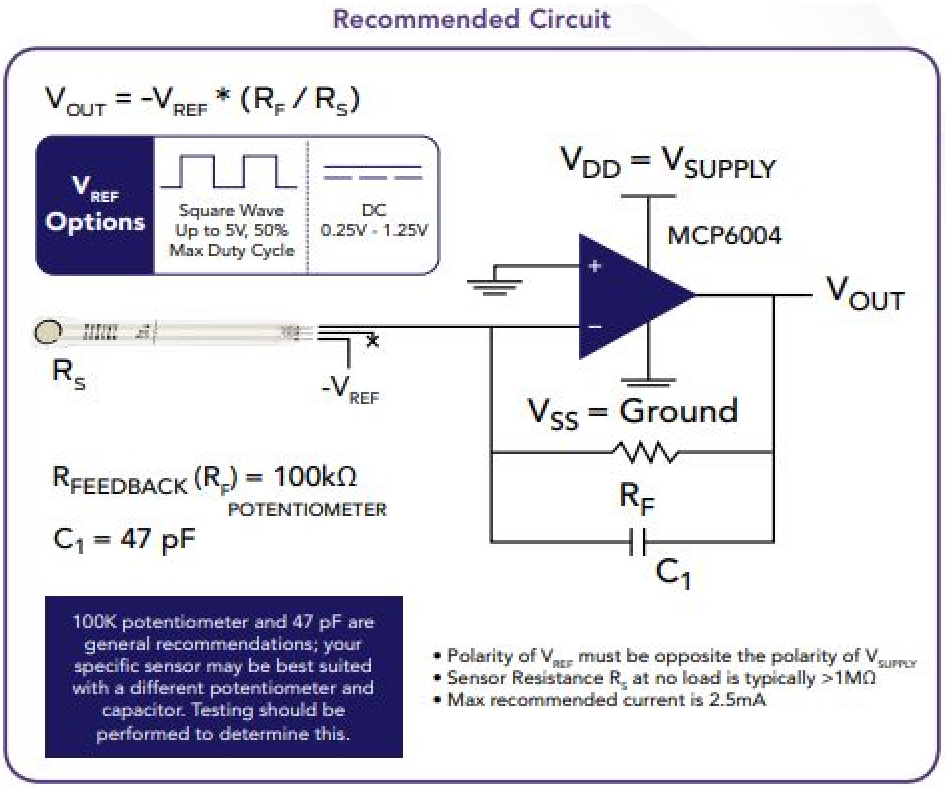


Figure 6: Recommended Circuit for FlexiForce Sensor

Using a breadboard, this circuit was mimicked by wiring the capacitor and resistor in series with the ground of the sensor and wiring the analog output of the sensor in series with the power source of the Arduino. The capacitor functions as a means to filter out noise from the other circuits and the resistor helps measure the change in resistance as the current runs through the circuit. This change in resistance occurs when a pressure is applied to the sensor area. A flexible membrane is sealed in the sensing portion of the sensor and when a force is applied the membrane deforms. This deformity causes a change in resistance as the current passes through it, which is subsequently measured in comparison to the resistor. The test subject placed their weight on the sensors and each sensor defromed a different amount, based on the distribution of weight under each point on the subject’s foot. These values were collected using the Arduino IDE software.

The sensor sends an analog signal back to the Arduino after the change in resistance occurs. The Arduino IDE accepts this analog code and converts it to a digital code and then converts the change in resistance to a measured weight. The code also went through an iteration of storing the max value each sensor experienced. Those max values were then copy and pasted into excel and the data was normalized for use in the 3D modeling.

2. Normalization of Data

In order to ensure a similar maximum and minimum thickness across a range of test subjects the data had to be normalized to create a relationship between the maximum voltage reading (the area where the most pressure is present) and the minimum height of the orthotic. This relationship is defined as a constant and is the product of the maximum voltage reading and the user defined minimum orthotic thickness. This is expressed mathematically in Equation (1).

$$C_1 = V_{max} * H_{min} \tag{1}$$

Once this constant value has been obtained for the specified test subject, all other voltage readings can be converted to orthotic thickness by using Equation (2).

$$H_i = C_1/V_i \tag{2}$$

Once all heights were obtained, it was observed that due to the large range of pressure values, the maximum height output was too large to comfortably fit in a normal shoe. To remedy this, equations 3 and 4 are used to finish normalizing the points.

$$C_2 = H_{MaxOut}/H_{MaxUser} \tag{3}$$

$$H_{iNew} = H_i/C_2 \tag{4}$$

Where, H_MaxOut is the initial normalized heights of the insole, and H_MaxUser is the user defined maximum height. This normalization was completed using Microsoft Excel. And data from test subjects 1 and 2 can be seen in the spreadsheets shown in Figure 7 and Figure 8, respectively. By comparison, it can be noted that by defining a maximum thickness of the orthotic, the overall height range for the orthotic is very similar between the two test subjects, despite the 45lbs weight range between them.

Data Input	
Data Point	Max Voltage Reading
1	2.727
2	2.386
3	0.597
4	0.199
5	0.568
6	1.619
7	0.483
8	1.818
9	0.227
10	1.42

Test Subject 1	
Weight (lbs)	155

Normalization Constant				
Max Voltage	Min Height	Max Height	C1	C2
=MAX(C4:C13)	User Defined	User Defined	=E8*F8	=F12/G8
2.727	0.0625	0.5	0.17044	1.71294

Height Range of Orthotic (Initial Data)	
Minimum Height (inches)	0.071
Maximum Height (inches)	0.856
Height Range of Orthotic (After Normalization)	
Minimum Height (inches)	0.036
Maximum Height (inches)	0.500

Data Output		
Data Point	Height (inches) (H_i)	Formula
1	0.063	=$H$8/C4
2	0.071	=$H$8/C5
3	0.285	=$H$8/C6
4	0.856	=$H$8/C7
5	0.300	=$H$8/C8
6	0.105	=$H$8/C9
7	0.353	=$H$8/C10
8	0.094	=$H$8/C11
9	0.751	=$H$8/C12
10	0.120	=$H$8/C13

Data Output		
Data Point	Height (inches) (H_iNew)	Formula
1	0.036	=L4/$I$8
2	0.042	=L5/$I$8
3	0.167	=L6/$I$8
4	0.500	=L7/$I$8
5	0.175	=L8/$I$8
6	0.061	=L9/$I$8
7	0.206	=L10/$I$8
8	0.055	=L11/$I$8
9	0.438	=L12/$I$8
10	0.070	=L13/$I$8

Figure 7: Data Normalization for Test Subject 1

Data Input	
Data Point	Max Voltage Reading
1	2.95
2	2.67
3	0.65
4	0.28
5	0.71
6	1.745
7	0.591
8	2.02
9	0.455
10	1.42

Test Subject 2	
Weight (lbs)	190

Normalization Constant				
Max Voltage	Min Height	Max Height	C1	C2
=MAX(C4:C13)	User Defined	User Defined	=E8*F8	=F12/G8
2.95	0.0625	0.5	0.184375	1.316964286

Height Range of Orthotic (Initial Data)	
Minimum Height (inches)	0.069
Maximum Height (inches)	0.658
Height Range of Orthotic (After Normalization)	
Minimum Height (inches)	0.047
Maximum Height (inches)	0.500

Data Output		
Data Point	Height (inches) (H_i)	Formula
1	0.063	=$H$8/C4
2	0.069	=$H$8/C5
3	0.284	=$H$8/C6
4	0.658	=$H$8/C7
5	0.260	=$H$8/C8
6	0.106	=$H$8/C9
7	0.312	=$H$8/C10
8	0.091	=$H$8/C11
9	0.405	=$H$8/C12
10	0.130	=$H$8/C13

Data Output		
Data Point	Height (inches) (H_iNew)	Formula
1	0.047	=L4/$I$8
2	0.052	=L5/$I$8
3	0.215	=L6/$I$8
4	0.500	=L7/$I$8
5	0.197	=L8/$I$8
6	0.080	=L9/$I$8
7	0.237	=L10/$I$8
8	0.069	=L11/$I$8
9	0.308	=L12/$I$8
10	0.099	=L13/$I$8

Figure 8: Data Normalization for Test Subject 2

3. 3D Modeling

Once the normalization of data was achieved, a 3D model had to be generated. The model was started by creating a proportional, 2-dimensional top view of a men’s size 10.5 foot. The outline was then extruded to a desired maximum height of 0.500 inches. Next, the contour of the top of the orthotic was generated by adjusting the height of the 10 discrete data points (as measured by the *FlexiForce* Pressure Sensors) and utilizing a lofted cut command.. Figure 9 depicts the original 2D projection of the foot and the discrete data points and planes used to generate the top contour of the orthotic.

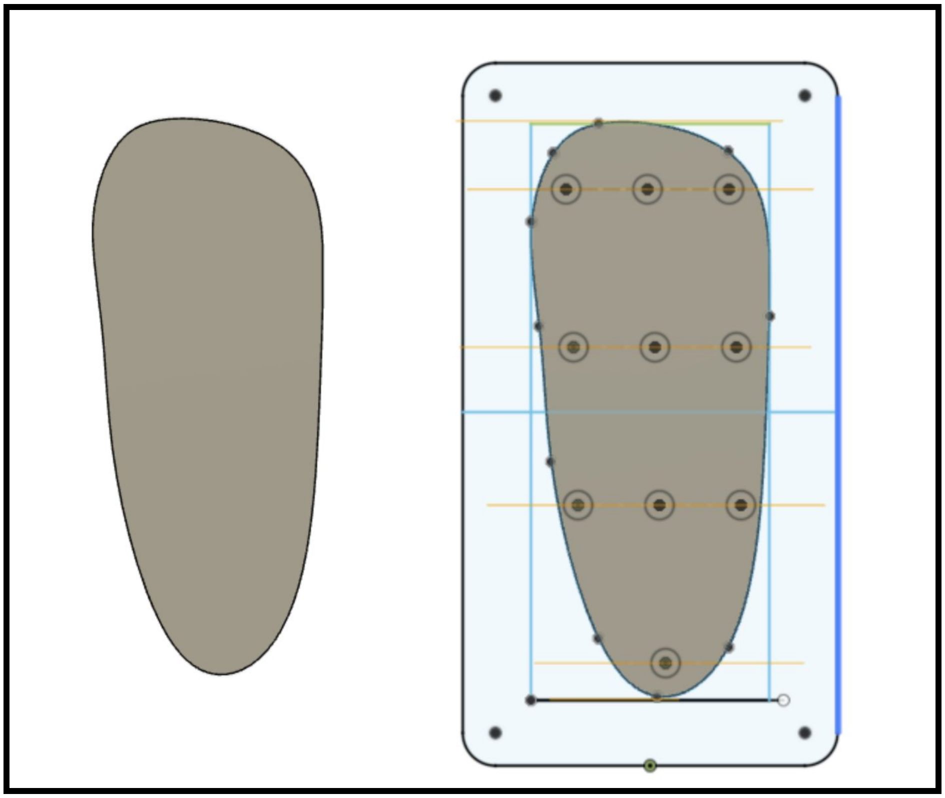


Figure 9: (Left) Top view of 2D, Proportional Foot. (Right) Discrete Data Points and Planes Used to Generate Contour

Figures 10 and 11 depict the process by which the discrete data points were used in multiple 2D sketches, and then a lofted cut was performed, respectively.

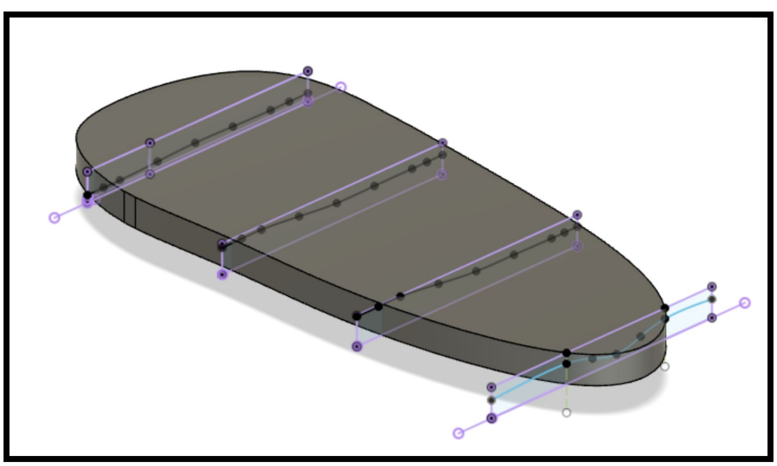


Figure 10: 2D Sketches Used to Create Contour

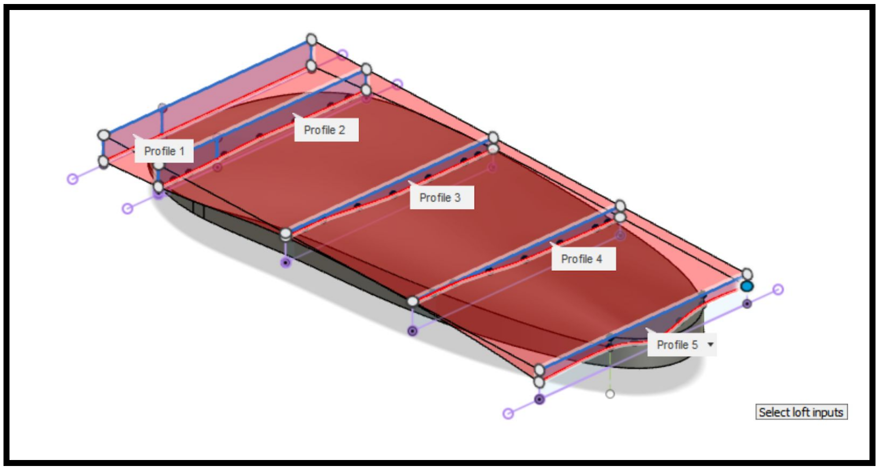


Figure 11: Lofted Cut Process

Figures 12, 13, and 14 show the right side view, front view, and isometric view of the orthotic generated for test subject 1. It can be seen in the photos that the lofted cut generated a smooth, supportive contour of the test subjects foot. This smooth curve is custom fit to the foot based on the data collected from the FlexiForce Pressure Sensors.

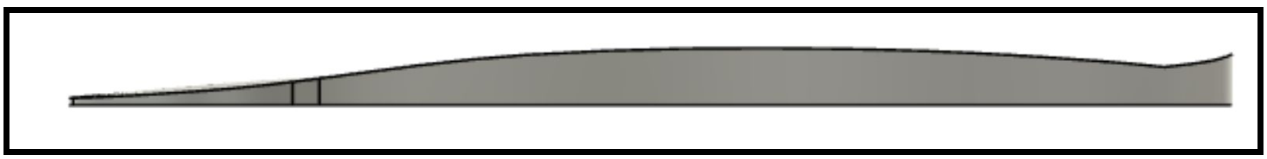


Figure 12: Right Side View of Test Subject 1 Orthotic

Figure 13: Front View of Test Subject 1 Orthotic

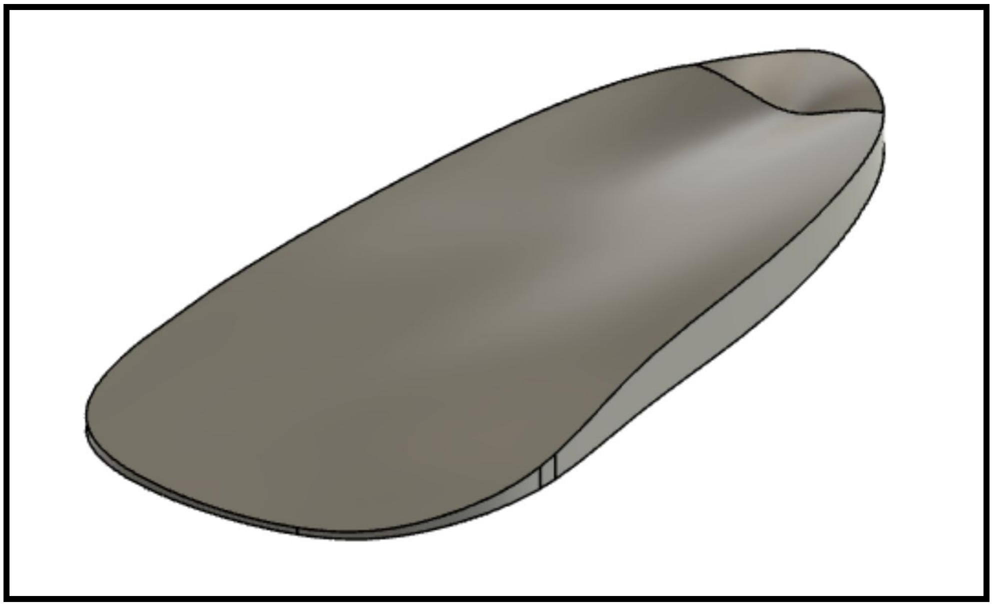


Figure 14: Isometric View of Test Subject 1 Orthotic

Once the model was generated, a simple desktop 3D printer (Monoprice Maker Select V2) was used to print the insole using a TPU filament. TPU is a rubber-like material, with a hardness similar to that of a pencil eraser. This hardness is approximately equivalent to a Shore D75. In contrast, the hardness of a traditional insole is Shore 00 30. In order to increase the comfort of this orthotic, the infill was set to 25 percent. The final 3D printed orthotic can be seen in Figure 15.

Figure 15: Final 3D Printed Orthotic

4. Validation

The goal of the prototype was to create an insole that would effectively redistribute the weight of the patient. Due to complications of the COVID-19 pandemic, only one test subject was able to be validated. Validation was accomplished by placing the orthotic back on the prototype sensor and asking the patient to step back on the sensor to measure their weight distribution. The data was input into a MATLAB code to plot the pressure distribution both with and without the orthotic. The results for test subject 1 can be seen in Figure 16.

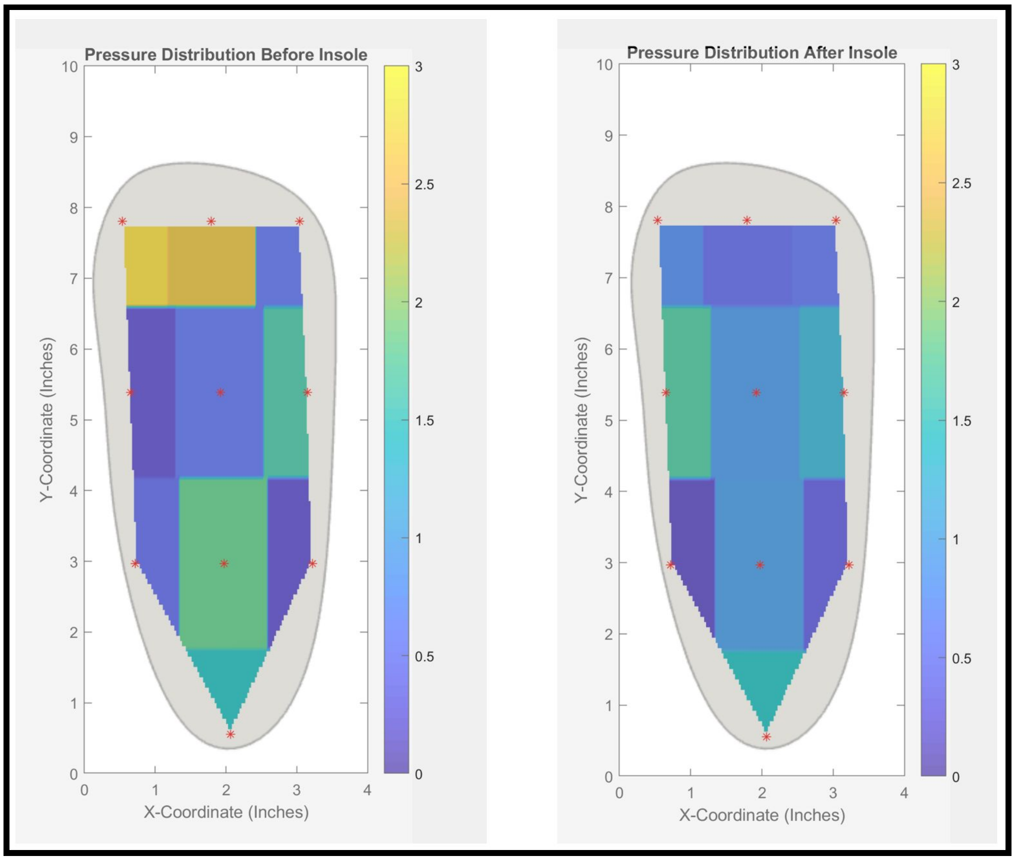


Figure 16: Validation of 3D Printed Orthotic

As seen in Figure 16, the pressure distribution after implementing the orthotic insole is considerably more consistent than before implementation of the insole. While this was the overall goal of the system, the insole itself was reported to be less comfortable than previously expected. Upon further research it was found that a totally even pressure distribution promotes flat footedness in patients. Further comments on this issue can be found in the “Conclusion” section.

Conclusion

A streamlined process for creating a 3D printed custom insole was developed by utilizing pressure sensors and 3D modeling. Data from the pressure sensors were used to develop a 3D model that evenly distributed the weight of the human body under the foot. Once the model was developed, it was 3D printed and validated to prove proper weight redistribution. Upon validation, it was proven that the insole did successfully redistribute the weight of the subject in a more consistent manner. Unfortunately, upon further investigation it was determined that evenly distributing the weight of the foot promotes flat footedness and is not the most comfortable distribution of weight. Moving forward it would be recommended to consult with a podiatrist and determine the most healthy and comfortable distribution of weight under the human foot. Armed with that knowledge, the normalization of the data could be adjusted to modify the model generation to make a model that would achieve this healthy, comfortable distribution.. Through comfortability testing and through validation of measuring the distribution of weight, the optimal design could be achieved to create the best custom, 3D printed insole. We were successful in achieving what was set out to do and to make the project more successful the recommendations of professionals in the area of podiatry would be needed. Additionally, the comfortability of the insole was not adequate for consumer use and a softer material is recommended, preferably Shore 00 30 hardness.

References

1. Huppin, Larry. “Dr. Scholl's Custom Fit Orthotics - Review by Seattle Podiatrist.” *Foot & Ankle*, 8 June 2019, www.footankle.com/a-review-of-dr-scholls-custom-fit-arch-supports-and-foot-mapping-machine/
2. Foot Orthotic Insoles Market to Reach 3.5 USD Billion By 2020

   IndustryARC

   https://www.prnewswire.com/news-releases/foot-orthotic-insoles-market-to-reach-35-usd-billion-by-2020-570502031.html
3. FlexiForce Load/Force Sensors and Systems

   https://www.tekscan.com/flexiforce-load-force-sensors-and-systems

Appendix

Pressure Distribution Map Code (MATLAB)

```
%% Kirtley/Wiles Senior Design
% Spring 2020
% Andrew Wiles, Dakota Kirtley
clc
clear
close all
[num,txt,raw] = xlsread('Matlab1.xlsx')
x = num(:,1) ;
y = num(:,2) ;
pressure = num(:,3) ;
x = x;
y = y ;
z = pressure ;
% Remove Nans in data
x = x(~isnan(y)) ;
z = z(~isnan(y)) ;
y = y(~isnan(y)) ;
nx = 100; ny = 100 ;
xi = linspace(min(x),max(x),nx) ;
yi = linspace(min(y),max(y),ny) ;
[X,Y] = meshgrid(xi,yi) ;
F = scatteredInterpolant(x,y,z,'nearest','none') ;
Z = F(X,Y) ;
pcolor(X,Y,Z);
axis equal
axis([0 4 0 10])
title('Pressure Distribution After Insole')
xlabel('X-Coordinate (Inches)')
ylabel('Y-Coordinate (Inches)')
shading interp ;
colorbar
caxis([0 3])
hold on
for i = 1:length(num)
   plot(num(i,1),num(i,2),'*','Color','Red')
   drawnow
end
```

Data Acquisition Code (Arduino IDE)

```
float cf = 4;
int ffs0 = A0; //analog pin 0
int ffs1 = A1; //analog pin 1
int ffs2 = A2; //analog pin 2
int ffs3 = A3; //analog pin 3
int ffs4 = A4; //analog pin 4
int ffs5 = A5; //analog pin 5
int ffs6 = A6; //analog pin 6
int ffs7 = A7; //analog pin 7
int ffs8 = A8; //analog pin 8
int ffs9 = A9; //analog pin 9
int ffsdata0 = 0, ffsdata1 = 0, ffsdata2 = 0, ffsdata3 = 0, ffsdata4 = 0, ffsdata5 = 0, ffsdata6 = 0, ffsdata7 = 0, ffsdata8
        = 0, ffsdata9 = 0;
float vout0, vout1, vout2, vout3, vout4, vout5, vout6, vout7, vout8, vout9;
float max0, max1, max2, max3, max4, max5, max6, max7, max8, max9;
void setup() {
  Serial.begin(9600);
  pinMode(ffs0, INPUT);
  pinMode(ffs1, INPUT);
  pinMode(ffs2, INPUT);
  pinMode(ffs3, INPUT);
  pinMode(ffs4, INPUT);
  pinMode(ffs5, INPUT);
  pinMode(ffs6, INPUT);
  pinMode(ffs7, INPUT);
  pinMode(ffs8, INPUT);
  pinMode(ffs9, INPUT);
}

void loop() {
  for (int i = 0; i <= 5; i++) {

    ffsdata0 = analogRead(ffs0);
    vout0 = ffsdata0/35.2;
    if (vout0 > max0) {
      max0 = vout0;
    }
    Serial.print("Flexi Force sensor 0: ");
    Serial.print(max0, 3);
    Serial.println("");
    delay(250);

    ffsdata1 = analogRead(ffs1);
    vout1 = ffsdata1/35.2;
    if (vout1 > max1) {
      max1 = vout1;
    }
    Serial.print("Flexi Force sensor 1: ");
```

```
Serial.print(max1, 3);
Serial.println("");
delay(500);

ffsdata2 = analogRead(ffs2);
vout2 = ffsdata2/35.2;
if (vout2 > max2) {
  max2 = vout2;
}
Serial.print("Flexi Force sensor 2: ");
Serial.print(max2, 3);
Serial.println("");
delay(250);

ffsdata3 = analogRead(ffs3);
vout3 = ffsdata3/35.2;
if (vout3 > max3) {
  max3 = vout3;
}
Serial.print("Flexi Force sensor 3: ");
Serial.print(max3, 3);
Serial.println("");
delay(250);

ffsdata4 = analogRead(ffs4);
vout4 = ffsdata4/35.2;
if (vout4 > max4) {
  max4 = vout4;
}
Serial.print("Flexi Force sensor 4: ");
Serial.print(max4, 3);
Serial.println("");
delay(250);

ffsdata5 = analogRead(ffs5);
vout5 = ffsdata5/35.2;
if (vout5 > max5) {
  max5 = vout5;
}
Serial.print("Flexi Force sensor 5: ");
Serial.print(max5, 3);
Serial.println("");
delay(250);

ffsdata6 = analogRead(ffs6);
vout6 = ffsdata6/35.2;
if (vout6 > max6) {
  max6 = vout6;
}
Serial.print("Flexi Force sensor 6: ");
```

```
    Serial.print(max6, 3);
    Serial.println("");
    delay(250);

    ffsdata7 = analogRead(ffs7);
    vout7 = ffsdata7/35.2;
    if (vout7 > max7) {
      max7 = vout7;
    }
    Serial.print("Flexi Force sensor 7: ");
    Serial.print(max7, 3);
    Serial.println("");
    delay(250);

    ffsdata8 = analogRead(ffs8);
    vout8 = ffsdata8/35.2;
    if (vout8 > max8) {
      max8 = vout8;
    }
    Serial.print("Flexi Force sensor 8: ");
    Serial.print(max8, 3);
    Serial.println("");
    delay(250);

    ffsdata9 = analogRead(ffs9);
    vout9 = ffsdata9/35.2;
    if (vout9 > max9) {
      max9 = vout9;
    }
    Serial.print("Flexi Force sensor 9: ");
    Serial.print(max9, 3);
    Serial.println("");
    delay(250);
  }
}
```